5.14 EXAMPLES OF NOISE INTERFERENCE ON DOPPLER SODAR PERFORMANCE

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1. INTRODUCTION

Since Doppler sodars utilize acoustic pulses to remotely sense the overlying wind field, the presence of ambient background noise can degrade data quality. Thus, special considerations must be made to avoid, or at least minimize noise interference. This can be a difficult challenge, especially in an urban setting where there are many sources of noise. Several examples of noise are shown in this paper.

2. THEORY OF OPERATION

Sodars operate on the principle of acoustic back-scattering. An electronic sound driver is used to generate an acoustic pulse into the atmosphere with a frequency typically between 1 and 5 kHz. The duration of each pulse is usually between 50 and 300 ms. As the sound wave propagates through the atmosphere, a small fraction of its energy is scattered back to the surface by small-scale temperature inhomogeneities whose scale is similar to that of the wavelength of the acoustic pulse.

The backscattered signal is amplified and digitally recorded at a rate of several hundred times per second over a period of several seconds. The time series is subdivided into smaller blocks, each representing a discrete layer in the atmosphere. Any number of algorithms are employed (Neff and Coulter 1986) to determine the mean frequency of the backscattered signal. The Doppler shift, that is to say the difference between the transmitted frequency and the backscattered frequency, is directly proportional to the radial wind velocity along the acoustic beam axis. Determination of the total wind vector requires a minimum of three independent radial wind velocities.

Sodars which use acoustic frequencies less than 2 kHz generally have a maximum sounding range of 1 to 2 km (Clifford et al. 1994). The range of a sodar using acoustic pulses greater than 2 kHz drops off dramatically with increasing frequency because of the effects of molecular attenuation. A sodar with a transmit frequency of 4 to 5 kHz has a range of about 200 to 300 m. However, most environmental noise tends to exhibit frequencies less than 2 kHz and its spectrum falls off sharply as frequency increases (Simmons et al. 1971). The challenge is attempting to find a balance which will maximize sodar range and minimize noise interference.

The limiting factor in wind velocity determination is usually the amount of environmental noise included with the backscattered signal (Neff and Coulter 1986). A sodar must be able to differentiate the Doppler-shifted backscattered signal from all other ambient background noise. These external noise sources can be classified as active or passive and as broad-band (i.e., white noise or random frequency) or narrow-band (fixed-frequency). In general, a poor signal-to-noise ratio generally increases the variance of Doppler estimates and biases the Doppler-shifted frequency of the backscattered signal toward zero (Gaynor 1977; Neff and Coulter 1986).

Most ambient background noise is active broad-band. Examples include highway and road traffic, heavy machinery, industrial facilities, power plants, and airplanes. These noise sources produce a wide-band signal which can overlap the frequency bandwidth used by a sodar. Active broad-band noise effectively decreases the signal-to-noise ratio which results in a decrease in the maximum vertical range of the sodar since the backscattered signal can not be discerned from the active broad-band noise. Higher range gates are more susceptible to being lost to noise interference because of the exponential decrease in backscattered power with

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height. In general, the performance of a sodar will degrade as noise levels increase from these nearby sources. Some active broad-band noise sources such as highway traffic may have a pronounced diurnal, weekly, or seasonal pattern.

Active fixed-frequency noise sources include the back-up beepers used on large trucks and forklifts, rotating fans, birds, and insects. These noise sources affect the performance of a sodar in different ways depending upon their type and proximity. If these noise sources have a frequency component in the sodar's operating range, they may be misinterpreted by the sodar as valid backscattered data. That is to say, the algorithms used to determine the Doppler-shifted frequency of the backscattered signal are fooled by the active fixed-frequency noise. The result is an erroneous wind value that may be found in any number of the measurement heights which depend on the arrival time of the noise in relation to the initial transmit time of the sodar. Since a sodar expects only a very weak backscattered signal, strong active fixed-frequency noise sources may saturate the received signal. When this happens, the sodar is unable to determine any value for wind velocity. Some of these sources can be identified during the site selection process. One approach to reducing the problem of fixed-frequency noise sources is to use a coded pulse, i.e., a pulse has more than one peak frequency. A return pulse would not be identified as data unless peak frequencies were found in the return signal the same distance apart as the transmit frequencies. Pinkel and Smith (1992) introduced a repeat-sequence coding technique for Doppler sonars and sodars which were found to increase the precision of velocity estimates.

Passive noise sources are objects that reflect a transmitted acoustic pulse back to the sodar antenna. Examples of potential reflectors include buildings, trees, towers, and transmission lines. While most of the transmitted acoustic energy is focused in a narrow beam, side lobes do exist. Substantial side lobe energy is generally associated with lower frequencies. Fixed-echoes are created when the side lobes reflect off of stationary objects and return the same acoustic frequency to the sodar receiver. A zero Doppler shift would be interpreted by the sodar as a valid wind speed of 0 m s^{-1}.

Algorithms have been developed which isolate and remove ambient background noise. Melling and List (1978) introduced a zero-crossing technique to extract wind velocities from the backscattered signal. Mastrantonio and Fiocco (1982) developed a technique to improve the accuracy and precision of sodar wind measurements by isolating the backscattered signal from ambient noise by a spectral integration. Good results have been obtained with a noise reduction scheme developed by Gardiner and Hill (1986). The final few samples of each received backscattered signal are assumed to be due entirely to wind noise. This provides a baseline which is subtracted out of the next backscattered signal. Some commercially available sodars have algorithms which identify fixed-echoes. In general, the algorithms would identify backscattered frequencies with zero Doppler shift which remain constant in space and over time. That peak frequency would be eliminated and the next strongest backscattered frequency would be selected to be used in determining the wind velocity.

Crescenti (1997) provided a review of numerous examples of noise interference with sodar operation cited in many sources of literature. Unfortunately, the assessment of data loss in these instances was more qualitative than quantitative. The following examples are an attempt to quantitative the nature of ambient noise.

3. EXAMPLES OF NOISE

Two case studies are presented which illustrate the affect of different forms of ambient noise on sodar operation. The spectral information shown was obtained using a program named Spectrogram (ver. 3.1) operating in a laptop based Windows 95 environment. At the time of this paper preparation the software was considered freeware and is available on the Internet. The program was originally developed for the purpose analyzing and identifying bird songs. Spectrogram has been used for many other investigations which include the analysis of other biological sounds (e.g., insects, amphibians, whales), electromagnetic disturbances, machinery, amateur radio signal analysis and speech identification.

During a recent large scale ozone study there were a number of sodars deployed to document the transport winds throughout the study domain. As part of a quality assurance audit program selected sites were surveyed prior system installation to determine the appropriateness for wind measurement using sodars and other remote sensors. One site was located adjacent to a water pumping station that had a series of pumps used for water distribution. The building housing the pumps was sound insulated so as to minimize the potential disturbance to adjoining neighbors. As part of the pre-survey a sampling of the background noise was performed to help identify any ambient noise sources that could cause problems in the operation of sodars. Figure 1 shows the typical spectra observed during sampling at one site.

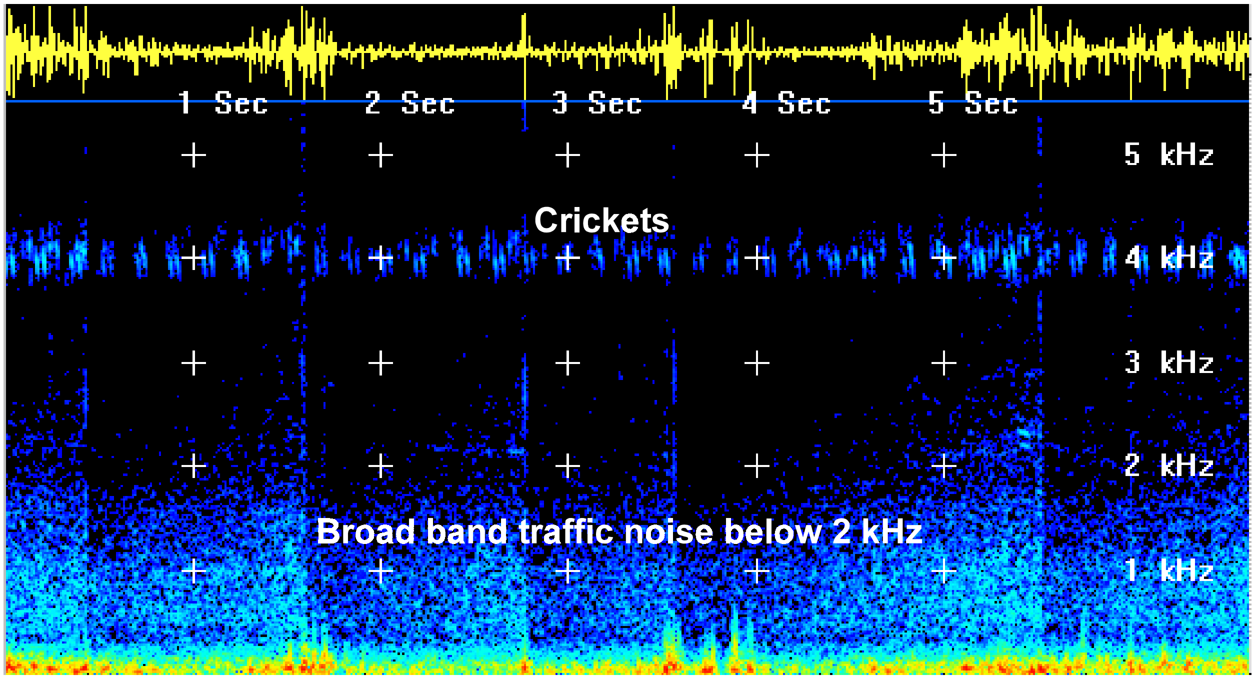

Figure 1. Spectra showing different forms of noise at a site during a pre-survey.

The spectra shown in the figure illustrates the noise band related to the traffic with strong intensities represented by brighter colors below 2 kHz. This broad band noise would be detrimental to sodar operations in that spectrum. Also observed at approximately 4 kHz, the noise generated by crickets in the brush surrounding the site would create significant noise for sodars operating in the 3.8 to 4.2 kHz range.

Subsequent to the survey, a sodar was installed and operation was started at a frequency of about 1.8 kHz. There was difficulty in obtaining reasonable data at that frequency due to the low frequency traffic noise and other potential sources, so new frequencies were explored and eventually 2.4 kHz was chosen for the operating frequency.

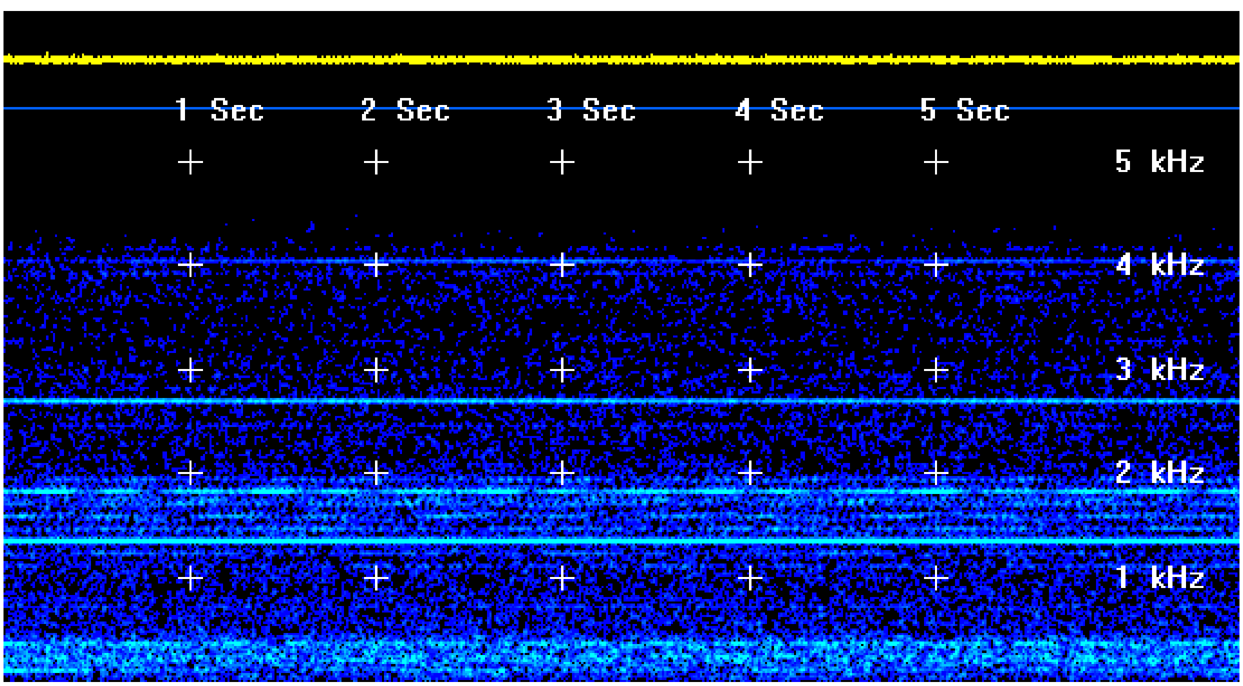

Figure 2. Spectra showing noise generated by the water pumps.

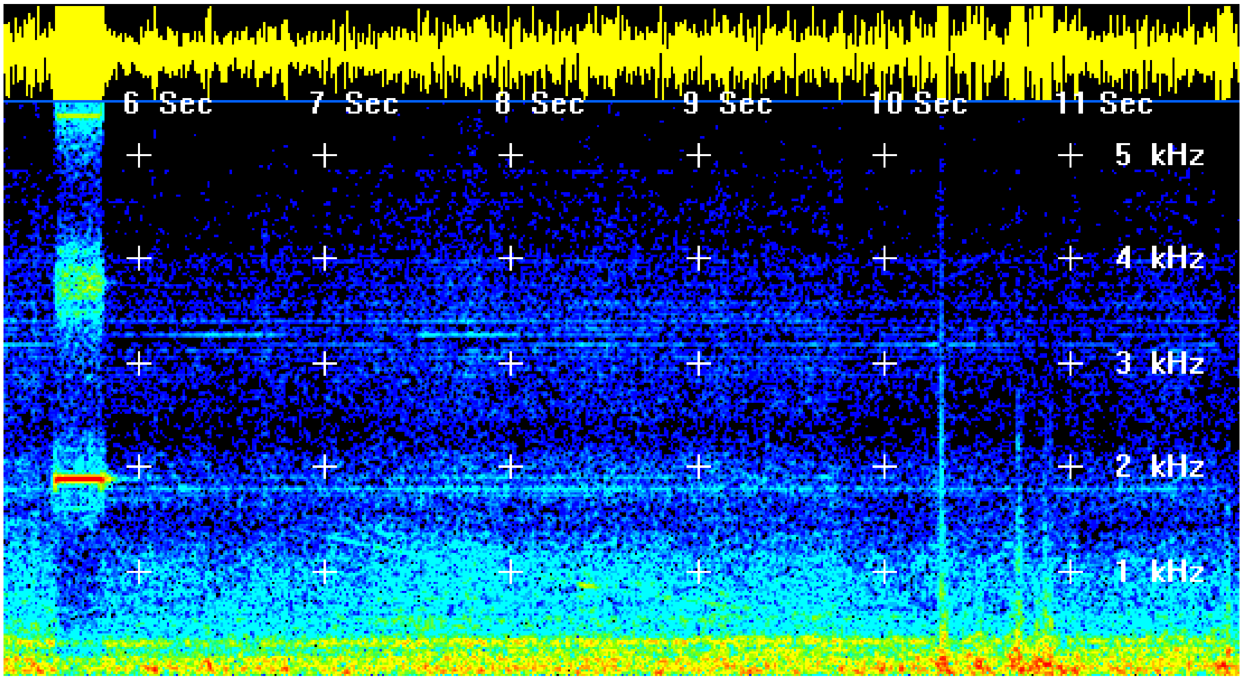

Figure 3. Noise spectra showing sodar transmit pulse and noise spectra from the air conditioner on an adjacent trailer.

Approximately two months later, the sodar was performance audited and a more detailed survey of the noise spectra generated from the pumps in the adjacent building was performed. Figure 2 shows the spectra obtained from the inside of the building near the pumps. A review of this spectra showed significant noise in the 1.3 to 2.0 kHz range. While the housing pumps of the building were acoustically insulated to minimize its noise, the sodar significantly amplifies received signals and most likely "heard" the undesired noise through the insulation. By "locking on" to a pump frequency, consistent profiles of wind could be erroneously recorded. By moving the sodar operation to 2.4 kHz, it was placed in a "null" of the pump noise spectrum.

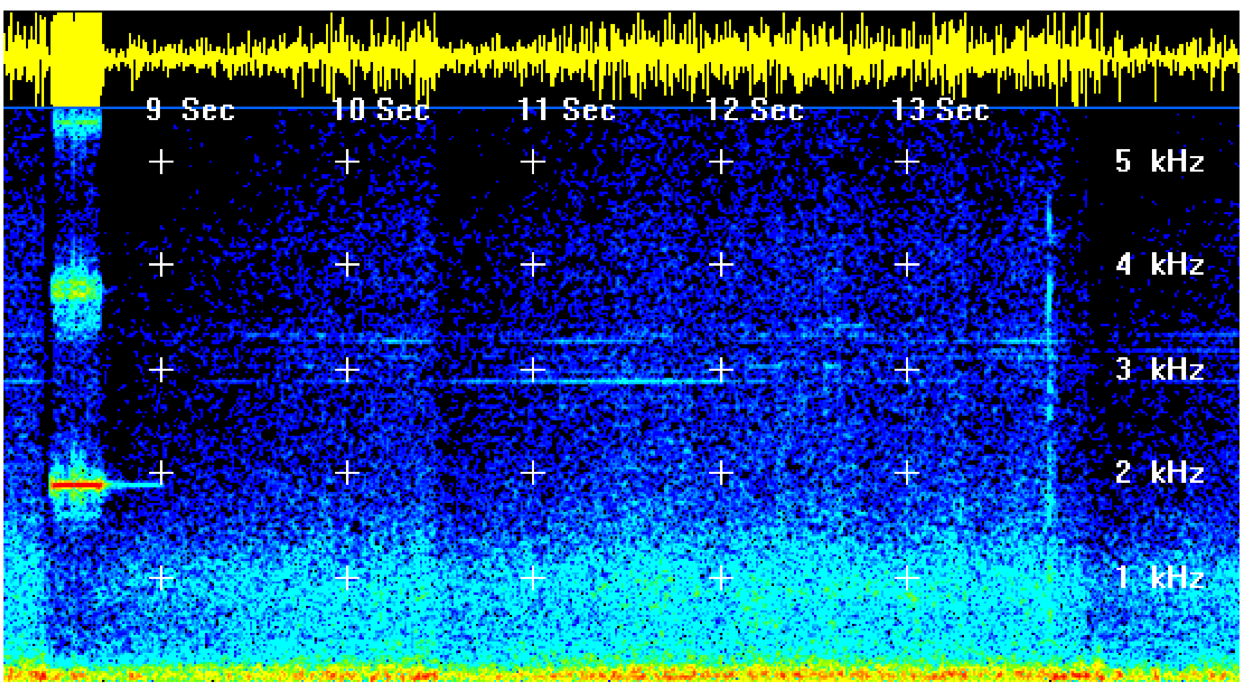

Figure 4. Noise spectra with the adjacent trailer air conditioner turned off.

In a second example, a sodar was operated within 5 m of a trailer that had a top mounted air conditioner. While the sodar was using software that selectively rejected fixed frequencies from such noise sources, unusual data was observed with unrealistically high vertical velocities during nighttime hours. Since the horizontal sodar winds were corrected for vertical velocity, erroneous vertical values would affect the accuracy of the resulting horizontal data. Figure 3 shows the spectra observed at the sodar antenna. The sodar transmit pulse can be seen at about 1.9 kHz as well as the background spectra close to the sodar frequency from the adjacent air conditioner. The air conditioner noise lines were as close as 11 Hz to the sodar transmit frequency.

Figure 4 shows the same site with the air conditioner turned off. The spectral lines around the transmit frequency are noticeably absent. The strong line immediately following the transmit pulse was a reflection from a local building.

4. SUMMARY

Background ambient noise has a significant effect on the operation of sodars. This paper has described various types of noise and how they may degrade the data collected. With the use of a simple PC based spectral analysis program, noise measurements were made during a sodar audit program to help understand the environmental noise that affects operations. This type of analysis, coupled with an understanding of how the noise will affect the sodar operations, provides a powerful tool for optimizing the siting and operation of sodars. The software used was obtained as freeware and is available on the Internet. Future use of such analysis tools will only improve the data collected from sodar based platforms.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Clifford, S. F., J. C. Kaimal, R. J. Lataitis, and R. G. Strauch, 1994: Ground-based remote profiling in atmospheric studies: An overview. *Proc. IEEE*, **82**, 313-355.

Crescenti, G. H., 1997: The degradation of Doppler sodar performance due to noise: a review. *Atmos. Environ.*, in press.

Gardiner, B. A., and M. K. Hill, 1986: Acoustic sounder observations from an elevated location. *Bound.-Layer Meteor.*, **36**, 307-316.

Gaynor, J. E., 1977: Acoustic Doppler measurement of atmospheric boundary layer velocity structure functions and energy dissipation rates. *J. Appl. Meteor.*, **16**, 148-155.

Mastrantonio, G., and G. Fiocco, 1982: Accuracy of wind velocity determinations with Doppler sodars. *J. Appl. Meteor.*, **21**, 823-830.

Melling, H., and R. List, 1978: Doppler velocity extraction from atmospheric acoustic echoes using a zero-crossing technique. *J. Appl. Meteor.*, **17**, 1274-1285.

Neff, W. D., and R. L. Coulter, 1986: Acoustic remote sensing. *Probing the Atmospheric Boundary Layer*, D. H. Lenschow, Ed., Amer. Meteor. Soc., 201-239.

Pinkel, R., and J. A. Smith, 1992: Repeat-sequence coding for improved precision of Doppler sonar and sodar. *J. Atmos. Oceanic Technol.*, **9**, 149-163.

Simmons, W. R., J. W. Wescott, and F. F. Hall, Jr., 1971: Acoustic echo sounding as related to air pollution in urban environments. NOAA Tech. Report ERL 216-WPL 17, Boulder, CO, 77 p.